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A Comparison of Supersymmetry Breaking and Mediation Mechanisms

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Abstract

We give a unified treatment of different models of supersymmetry breaking and mediation from a four dimensional effective field theory standpoint. In particular a comparison between GMSB and various gravity mediated versions of SUSY breaking shows that, once the former is embedded within a SUGRA framework, there is no particular advantage to that mechanism from the point of view of FCNC suppression. We point out the difficulties of all these scenarios - in particular the cosmological modulus problem. We end with a discussion of possible string theory realizations.

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1 Introduction

In this note we will give a unified treatment of the various alternatives that have been proposed in the literature for supersymmetry breaking and its mediation to the visible sector. The latter will be taken to be the minimally supersymmetric standard model (MSSM) though the arguments can be trivially generalized to extensions of the MSSM.

The first and oldest is mSUGRA (for a recent review see [1]). This theory uses the fact that a general supergravity (SUGRA) can have chiral scalar fields which are neutral under the standard model (SM) gauge group. Supersymmetry breaking happens when at the minimum of the potential for these moduli, some of them will acquire SUSY breaking values (i.e. their F-terms get non-zero values). This is communicated to the visible sector by the moduli, which couple with gravitational strength to the visible (MSSM) sector. Essentially the point is that in general when the MSSM is embedded in SUGRA, the Yukawa couplings as well as the gauge couplings will be functions of the moduli. In the low energy theory these will essentially act as spurion fields that generate a set of soft supersymmetry breaking terms at some high scale - typically taken to be the GUT scale. However a generic SUGRA will not yield a set of universal SUSY breaking parameters, so that experimental constraints on flavor changing neutral currents (FCNC) will rule out many such models. mSUGRA postulates that a sub-class of models will generate such a set. One of the aims of this work is to identify this sub-class and see whether it can be justified in terms of string theory. The scale of the soft terms is set by the value of the gravitino mass $m_{3/2}$. Thus if SUSY is to solve the gauge hierarchy problem this mass should be of the order of a few hundred GeV . This gives a natural explanation of the so-called μ -problem but this value of the gravitino mass is known to be cosmologically problematic. The associated light modulus (the scalar partner of the Goldstino) will also cause cosmological problems.

A variant of mSUGRA is a class of models in which the classical supersymmetry breaking parameters generated in mSUGRA are suppressed, so that the soft terms are essentially generated by quantum anomaly effects. These are often called sequestered models. In the original version of this scenario (called anomaly mediated supersymmetry breaking - AMSB) [2, 3], it was argued that both gaugino masses and slepton and squark masses were generated by these effects. However as was pointed out in [4] (based on the work of [5]) the Weyl anomaly, while generating gaugino

masses, cannot directly affect the soft scalar masses¹. These can however be generated by the non-zero gaugino masses through renormalization group (RG) evolution down from the high scale to the weak scale - a mechanism which is usually called gaugino mediated supersymmetry breaking (inoMSB) [7, 8]. A class of string theoretic models where this combined mechanism is operative was discussed in [9]. The detailed phenomenology has been worked out in [10] where this mechanism was called inoAMSB. Since in this class of theories the classical soft terms (as well as high scale quantum corrections) are suppressed and the anomaly and RG running effects are flavor diagonal, there are no FCNC problems. The salient feature of this class of theories is that, since the soft parameters are typically suppressed by a loop factor compared to $m_{3/2}$, the latter has to be taken at a scale around $100TeV$. This avoids the cosmological gravitino problem of mSUGRA. Nevertheless there is a cosmological modulus problem (unless we increase the fine-tuning in the little hierarchy) as we discuss later, and we also lose the natural solution to the μ problem.

The third class of theories is called gauge mediated supersymmetry breaking (GMSB) (for a review see [11]). In almost all of the discussions of GMSB, the question of embedding within supergravity is not discussed. The essential motivation for this class of theories is the need to find a natural solution to the FCNC problem. Thus it is postulated that supersymmetry breaking (which takes place in some hidden sector) is transmitted to the visible sector by gauge interactions. These theories must of course still be embedded in a supergravity and thus in order to avoid soft parameters generated by mSUGRA or its variants, it has to be assumed that the gravitino mass is well below the weak scale. Typically it is taken to be below the KeV scale in order to avoid cosmological problems. However now there is no natural solution to the μ problem and furthermore there is a $B\mu$ problem as well.

In the next section we will present the basic formulae which give us a general framework for discussing all of these theories from a unified perspective. In the subsequent sections we will take

¹The Weyl anomaly only affects the gauge kinetic terms (at the two derivative level) and hence only gives a correction to the gauge coupling superfield which then leads to Weyl anomaly generated contributions to the gaugino mass. The latter is given by the expression for the gaugino mass given in equation (G.2) of Wess and Bagger [6], once the Kaplunovsky Louis formula [5] for the gauge coupling function is used. The argument in the literature for a contribution to the soft mass and the A -term depends on inserting factors of the Weyl compensator into the wave function renormalization. This has no justification whatsoever. A physical result cannot depend on the particular formalism of SUGRA that is used and should be derivable, for instance, in the formalism used in Wess and Bagger [6] (where this particular auxiliary superfield is set equal to unity). This is possible for the correction to the gauge coupling function but there is no analog of this for the wave function renormalization. For details see [4].

up these three classes and present their theoretical underpinnings and discuss their possible string theory origin.

2 Generalities

We set $M_P = (8\pi G_N)^{-1} = 2.4 \times 10^{18} \text{GeV} = 1$. Let the gauge neutral moduli (some of which will acquire non zero vacuum values to break SUSY) be denoted by $\Phi = \{\Phi^A\}$. We expand the superpotential and the Kaehler potential in powers of the chiral superfields C^α which represent the visible sector (MSSM/GUT) fields. The coefficients of this expansion will be functions of the moduli Φ . So we write respectively, the superpotential, Kaehler potential and gauge kinetic function for the theory under discussion as,

$$W = \hat{W}(\Phi) + \frac{1}{2}\tilde{\mu}_{\alpha\beta}(\Phi)C^\alpha C^\beta + \frac{1}{6}\tilde{Y}_{\alpha\beta\gamma}(\Phi)C^\alpha C^\beta C^\gamma + \dots, \quad (1)$$

$$K = \hat{K}(\Phi, \bar{\Phi}) + \tilde{K}_{\alpha\bar{\beta}}(\Phi, \bar{\Phi})C^\alpha C^{\bar{\beta}} + [Z_{\alpha\beta}(\Phi, \bar{\Phi})C^\alpha C^\beta + h.c.] + \dots \quad (2)$$

$$f_a = f_a(\Phi). \quad (3)$$

The effective theory valid at some high scale well below the Planck/string scale, should be such that the potential for the moduli has at least one supersymmetry breaking minimum with nearly zero cosmological constant. This of course requires fine-tuning of some parameters, or an appropriate choice of internal fluxes in string theory constructions. Then the softly broken globally supersymmetric low energy theory is described in terms of an effective superpotential

$$W^{(eff)}(C) = \frac{1}{2}\mu_{\alpha\beta}C^\alpha C^\beta + \frac{1}{6}Y_{\alpha\beta\gamma}C^\alpha C^\beta C^\gamma + \dots, \quad (4)$$

and the SUSY breaking terms (with c denoting the lowest component of C)

$$\Delta V^{(eff)}(c) = m_{\alpha\bar{\beta}}^2 c^\alpha c^{\bar{\beta}} + \left(\frac{1}{2}(B\mu)_{\alpha\beta} c^\alpha c^\beta + \frac{1}{6}A_{\alpha\beta\gamma} c^\alpha c^\beta c^\gamma + h.c.\right). \quad (5)$$

The effective SUSY and SUSY breaking parameters are then given by [12] (assuming the CC is tuned to zero),

$$\mu_{\alpha\beta} = e^{\hat{K}/2} \tilde{\mu}_{\alpha\beta} + m_{3/2} Z_{\alpha\beta} - \bar{F}^{\bar{A}} \partial_{\bar{A}} Z_{\alpha\beta}, \quad (6)$$

$$Y_{\alpha\beta\gamma} = e^{\hat{K}/2} \tilde{Y}_{\alpha\beta\gamma} \quad (7)$$

$$B\mu_{\alpha\beta} = F^A D_A \mu_{\alpha\beta} - m_{3/2} \mu_{\alpha\beta}, \quad (8)$$

$$M_i = \frac{F^A \partial_A H_i}{2H_a}, \quad (9)$$

$$m_{\alpha\bar{\beta}}^2 = m_{3/2}^2 \tilde{K}_{\alpha\bar{\beta}} - F^A F^{\bar{B}} R_{A\bar{B}\alpha\bar{\beta}}, \quad (10)$$

$$A_{\alpha\beta\gamma} = F^A D_A Y_{\alpha\beta\gamma}, \quad (11)$$

with $D_A \equiv \nabla_A + K_A/2$ where ∇_A is the usual covariant derivative. In the above all the moduli are to be fixed at the SUSY breaking minimum. It should be emphasized that the Kaehler potential that is to be used in these formulae should be the effective Kaehler potential at the high scale - i.e. it should include all quantum corrections at that scale. On the other hand the Weyl anomaly will change the gauge coupling function from the classical function $f(\Phi)$ to the effective gauge coupling function $H(\Phi)$. The correct formula for this replacement is [5]

$$f_i \rightarrow H_i = f_i - \frac{3c_i}{8\pi^2} \tau - \sum_r \frac{T_i(r)}{4\pi^2} \tau_r - \frac{T(G_i)}{4\pi^2} \tau_i, \quad (12)$$

where the τ 's are various chiral rotations which are fixed by the following expressions:

$$\tau + \bar{\tau} = \frac{1}{3} K|_{\text{harm}}, \quad (13)$$

$$\tau_r + \bar{\tau}_r = \ln \det \tilde{K}_{\alpha\bar{\beta}}^{(r)}, \quad (14)$$

$$\exp[-(\tau_i + \bar{\tau}_i)]|_{\text{harm}} = \frac{1}{2} (H_i + \bar{H}_i). \quad (15)$$

In the above $|_{\text{harm}}$ is an instruction to keep only the chiral plus anti-chiral components of the relevant expressions.

The entire phenomenological content at some high scale (GUT scale/string scale or messenger

scale) of all theories of SUSY breaking and transmission are contained in the formulae (6) to (12). In the following we will elaborate on this statement.

3 SUGRA assumptions

Here we will discuss the assumptions at the supergravity level that lead to the various mechanisms of SUSY breaking and mediation. In the next section we will examine to what extent these assumptions can be justified from string theory.

3.1 mSUGRA

mSUGRA is phenomenologically defined by a set of input parameters at some high scale - typically chosen to be the GUT scale. Thus one chooses a universal value m_0 for the soft masses, another universal parameter A_0 for the scalar Yukawa couplings (i.e. $A_{\alpha\beta\gamma} = A_0 Y_{\alpha\beta\gamma}$), and a universal gaugino mass M . The μ parameter, as we observed earlier, comes out to be of the right order when we choose $m_{3/2} \sim m$ at the weak scale, and in mSUGRA phenomenology its exact magnitude is fixed by demanding the right Z mass, leaving the sign of μ as a parameter. $B\mu$ however is traded for $\tan\beta$, the ratio of the two Higgs vev's.

From a SUGRA point of view, a sufficient condition for the mSUGRA universality choice for the scalar masses is obtained, by simply demanding that the Kaehler metric on moduli space in the visible sector directions is conformal to a flat (moduli independent) metric. i.e.

$$\tilde{K}_{\alpha\bar{\beta}} = g(\Phi, \bar{\Phi}) k_{\alpha\bar{\beta}}, \quad (16)$$

where $k_{\alpha\bar{\beta}}$ is a constant matrix. In this case $R_{A\bar{B}\alpha\bar{\beta}} = \partial_A \partial_{\bar{B}} \ln g(\Phi, \bar{\Phi}) K_{\alpha\bar{\beta}}$ so that from (10)

$$m_{\alpha\bar{\beta}}^2 = (m_{3/2}^2 - F^A \bar{F}^{\bar{B}} \partial_A \partial_{\bar{B}} \ln g(\Phi, \bar{\Phi})) K_{\alpha\bar{\beta}}. \quad (17)$$

To get scalar Yukawa couplings proportional to the original ones, a sufficient additional assumption is that the original Yukawa couplings \tilde{Y} are independent of the SUSY breaking moduli ². In this

²Note that these conditions are considerably weaker than what is usually assumed as being a set of sufficient

case (since from (16) $\Gamma_{A\beta}^\alpha = \partial_A \ln g \delta_\beta^\alpha$) we have from (11)

$$A_{\alpha\beta\gamma} = F^A \left(\frac{1}{2} K_A + \partial_A \ln g(\Phi, \bar{\Phi}) \right) Y_{\alpha\beta\gamma} \equiv A_0 Y_{\alpha\beta\gamma}. \quad (18)$$

Finally to get universal gaugino masses (as is usually assumed in mSUGRA) one needs to assume that the gauge coupling functions of the three factors of the standard model gauge group have the same dependence on the (SUSY breaking) moduli. However although this assumption can in fact be realized in some string theoretic constructions, it is not crucial since non-universal gaugino masses at the high scale do not violate any phenomenological constraint. But leaving that aside, the simple assumption (16) and the assumption of Φ independence of the Yukawa couplings (for Φ 's which break SUSY at the $m_{3/2}$ scale, give a viable phenomenology and a testable set of predictions for LHC physics. The essential feature is that the scalar masses and the A , $B \equiv B\mu/\mu$ and μ terms are all generated at the scale of the gravitino $m_{3/2}$.

However this scenario appears to have cosmological problems (for a recent discussion of the cosmological gravitino and moduli problem with references to the earlier literature see [14]). In mSUGRA the gravitino mass is taken to be at the weak scale whereas to avoid conflicts with the standard Big Bang Nucleosynthesis (BBN) scenario the gravitino mass (as well as the lightest modulus) should be heavier than about $10TeV$. This would also entail a cosmological modulus problem since the scalar partner of the Goldstino (the sGoldstino) generically has a mass which is of the same order as the gravitino (see for example [15]).

3.2 Sequestered mSUGRA Models

This class of models is characterized by the cancellation of the leading terms that contribute to the soft terms. This means that at the high (GUT?) scale we should have

$$m_{\alpha\bar{\beta}}^2 = (m_{3/2}^2 \tilde{K}_{\alpha\bar{\beta}} - F^A F^{\bar{B}} R_{A\bar{B}\alpha\bar{\beta}}) \ll m_{3/2}^2 \tilde{K}_{\alpha\bar{\beta}}, \quad (19)$$

$$A_{\alpha\beta\gamma}|_{classical} = F^A D_A Y_{\alpha\beta\gamma} \ll m_{3/2} Y_{\alpha\beta\gamma}. \quad (20)$$

The point is that potentially FCNC violating terms generated at the high (GUT?) scale are

conditions for mSUGRA - see for example [13].

suppressed along with the flavor diagonal terms. The gaugino masses are generated by Weyl anomaly effects even if the classical terms are zero. The soft scalar masses and the A -terms are then generated through Renormalization Group (RG) running down to the MSSM scale. Obviously the requirement imposes a restriction on the moduli dependence of the Kaehler metric of the visible sector $\tilde{K}_{\alpha\bar{\beta}}$. The question is whether the class of models where this restriction holds is more natural (or more plausible) than the mSUGRA restriction discussed in the previous subsection. What we will argue later is that from the string theory point of view at least, there is a viable class of models in which this scenario can be quite explicitly realized.

In this class of models the gaugino masses, the scalar masses, as well as the A and B terms at the MSSM scale, are of order $(\alpha/4\pi)m_{3/2} \sim 10^{-2}m_{3/2}$ for a typical gauge coupling. To get weak scale soft terms then we need $m_{3/2} \sim 10 - 100 TeV$. This will eliminate the cosmological gravitino problem which afflicts mSUGRA. However in typical realizations of this scenario there is a potential μ problem. As can be seen from (6) generically a gravitino mass of $10 TeV$ or more will generate a μ term which is far too large. However in situations where sequestering is realized, the leading contributions to the last two terms of (6) will cancel. The question then is whether the subleading terms will generate a large enough μ term, when the $\tilde{\mu}$ term coming from the superpotential (1) of the fundamental theory is zero (as is the case in IIB models with the MSSM on a stack of D3 branes).

3.3 Gauge Mediated SUSY Breaking (GMSB)

GMSB is usually discussed within the context of global supersymmetry - with the gravitino mass and the tuning of the CC tacked on as an afterthought. But a complete supersymmetric effective theory, valid at say the GUT scale and below, must necessarily be a SUGRA. The main argument in favor of GMSB is that, since the hidden sector SUSY breaking is transmitted by gauge interactions to the visible sector, the soft terms do not generate FCNC effects. It is obviously crucial then to suppress potentially flavor violating effects generated by SUGRA effects. In GMSB models this is effected simply by suppressing the gravitino mass well below the weak scale - typically it needs to be at the KeV scale in order to avoid cosmological problems. However this means that the mechanism of SUSY breaking and transmission becomes more complicated. Essentially the

problem is that the typical modulus in a SUGRA has Planck scale vacuum expectation values (vev's). However in GMSB the chiral scalar or scalars in the effective O'Rafferteagh type models that are responsible for the SUSY breaking, are required to get vev's which are several orders of magnitude smaller than the Planck scale. Let us review briefly why this is the case.

Let X be the chiral scalar superfield that is responsible for breaking SUSY, i.e. at the minimum of the potential $F^X|_0 \neq 0$. We can without loss of generality for the purposes of this discussion, take this to be a single superfield so that³ $F^A|_0 = 0$ for $A \neq X$. The requirement that the CC is zero means

$$V_0 = |F^X|_0^2 - 3m_{3/2}^2 = 0, \quad (21)$$

so that $|F^X|_0 = \sqrt{3}m_{3/2}$.⁴ However as discussed above, the way GMSB suppresses possible FCNC effects coming from SUGRA is by taking $m_{3/2} = e^{K/2}|W|_0$ to be extremely small. i.e. effectively by choosing parameters in the superpotential such that in Planck units (for instance if the Kaehler potential is $O(1)$) $|W|_0 \lesssim 10^{-24}$. This is certainly possible in string theoretic constructions (for example in type IIB models) and we will come back to this issue later. But this means that (as we can see immediately from equations (9)(10)) the classically generated soft terms are negligible, and we need some mechanism for enhancing the relevant connection and curvature components of the matter metric. Essentially we need a singularity at the origin of moduli space to enhance the tiny value of F^X . In typical GMSB models this is achieved by coupling X to a so-called messenger sector (with superfields f, \tilde{f} say) taken to be in a vector-like representation of the standard model gauge group. Thus a term

$$\Delta W = X f \tilde{f}, \quad (22)$$

is added to the superpotential. Below the messenger scale X_0 one may integrate out the messengers. This gives a threshold effect at the messenger scale and contributes a term [16]

$$\Delta H = \sum_{r=f, \tilde{f}} \frac{T_i(r)}{4\pi^2} \ln X, \quad (23)$$

³In the following the subscript $|_0$ indicates that the corresponding quantity is to be evaluated at the relevant local minimum of the potential.

⁴If there are other sources of SUSY breaking which do not couple to the messengers this is an upper bound.

to the gauge coupling function at scales below the messenger scale. Consequently there is a contribution to the gaugino mass:

$$M_i = \sum_{r=f,\tilde{f}} T_i(r) \frac{g_i^2}{8\pi^2} \frac{F^X}{X}. \quad (24)$$

Now since $F^X \sim m_{3/2} \ll 100 GeV$ in order to get an acceptable gaugino mass, the vev of X needs to be suppressed well below its natural scale in SUGRA, i.e. the Planck scale. A similar enhancement happens in the curvature term contributing to the soft scalar mass (10) leading to a flavor diagonal contribution

$$m_{\alpha\bar{\beta}}^2 = m_0^2 K_{\alpha\bar{\beta}}, \quad m_0^2 = 2 \sum_i c_i \left(\frac{\alpha_i}{4\pi} \right)^2 \sum_{r=f,\tilde{f}} T_i(r) \left| \frac{F^X}{X} \right|^2. \quad (25)$$

In various versions of GMSB (direct, indirect, semi-direct, general) the hidden sector and the messenger sector may undergo modifications/generalizations so that the effective source of SUSY breaking F^X/X may be replaced by a sum of such terms. But the basic requirement (given that the F terms are at most of $O(m_{3/2})$) is that the vev's of the supersymmetry breaking hidden sector field or fields, need to be stabilized at some scale that is well below the Planck scale. For simplicity we will continue to assume that there is just the one SUSY breaking modulus X .

Most works on GMSB do not discuss the embedding of the theory within SUGRA. However as we've argued above, a theory of SUSY breaking cannot ignore SUGRA. The only attempt at a GMSB discussion within SUGRA that the author is aware of is that of [17]. The model is defined by the Kaehler potential,

$$K = X\bar{X} - \frac{(X\bar{X})^2}{\Lambda^2} + f\bar{f} + \tilde{f}\bar{\tilde{f}} + K_{MSSM}, \quad (26)$$

and superpotential

$$W = c + \mu^2 X + \lambda X f \tilde{f} + W_{MSSM}. \quad (27)$$

Here the superfields f, \tilde{f} are to be identified as the messengers of GMSB. The model has a true minimum (i.e. with no tachyons or flat directions) with the fields taking values $X_0 = \frac{\sqrt{3}\Lambda^2}{6}$, $f =$

$\tilde{f} = 0$, provided that $\Lambda^4 > \frac{12\mu^2}{\lambda}$ and the CC is tuned to zero; i.e.

$$\mu^2 \simeq \sqrt{3}c = \sqrt{3}m_{3/2}. \quad (28)$$

Using the standard mass formula for scalar masses in SUGRA the mass matrices may be evaluated. The scalar messengers have squared masses

$$\frac{\lambda^2 \Lambda^4}{12} \pm \lambda \mu^2 \quad (29)$$

while the scalar partner of the Goldstino (sGoldstino) has a mass $m_X \simeq 2\mu^2/\Lambda$. Finally the SUSY breaking is characterized by

$$F^X \simeq \mu^2 = \sqrt{3}m_{3/2}, \quad (30)$$

so that the relevant mass parameter determining soft terms in GMSB is (restoring M_P for clarity)

$$m \sim \frac{\alpha}{4\pi} \frac{F^X}{X} \simeq \frac{\alpha}{4\pi} \frac{M_P^2}{\Lambda^2} 6m_{3/2}. \quad (31)$$

This simple model illustrates several features that must generically be present in GMSB. Firstly, as we discussed before, the gravitino mass needs to be well below the weak scale in order to suppress the naturally occurring gravity (moduli) mediated contribution. The first factor in (31) gives a suppression of $O(10^{-2})$, so if we choose $m_{3/2} \lesssim 1\text{KeV}$ in order to avoid gravitino cosmological problems (as is usually done), then we must have a cutoff $\Lambda \lesssim 10^{-5}M_P$. Also we need to impose the CC fine tuning condition (28).

This scenario has a cosmological modulus problem. One might expect this [18] from the expression for the sGoldstino mass given in Covi et al [15], however that assumes that the only relevant scale is the the Planck scale. With a Kaehler potential as in (26) however there is a scale Λ which is significantly lower than the Planck scale. This has the potential of raising the sGoldstino mass above this bound. Nevertheless as we will argue below it cannot be raised high enough to evade cosmological problems.

Using (30) we can rewrite the mass of the sGoldstino (see below eqn.(29)) as

$$m_X \simeq 2\sqrt{3}m_{3/2}\frac{M_P}{\Lambda}. \quad (32)$$

On the other hand from (31), we have $\Lambda/M_P = (6\alpha m_{3/2}/4\pi m)^{1/2}$, so that from (32) we get

$$m_X = 2\sqrt{3}m_{3/2}\left(\frac{4\pi m}{6\alpha m_{3/2}}\right)^{1/2} \sim 10\sqrt{m_{3/2}m}. \quad (33)$$

In the last relation we have used $\alpha/4\pi \sim 10^{-2}$. Even for the largest allowed gravitino mass $\sim 1\text{KeV}$, if we take the soft mass scale m to be at the weak scale ($M_W \sim 100\text{GeV}$), this gives a modulus mass around 0.1GeV which is far too small to evade the modulus problem⁵. In fact to satisfy the bound on the modulus $m_X \gtrsim 10\text{TeV}$ we would need to take the soft mass scale $m \sim 10^{12}\text{GeV}$ which of course would be incompatible with a SUSY solution to the hierarchy problem.

3.4 GMSB - mSUGRA comparison

How does the previous scenario compare with the corresponding mSUGRA one. Firstly ignoring any fundamental (say string theory based) derivation, one could take the same starting point as the model (26)(27) except for two ingredients: one does not need the messenger sector, and the gravitino mass should have a weak scale value i.e. around $100 - 1000\text{GeV}$. In the next section we will look at string theory scenarios but here let us focus on using the same SUGRA embedding as in the GMSB case discussed above. So we take

$$K = X\bar{X} - \frac{(X\bar{X})^2}{\Lambda^2} + g(X, \bar{X})k_{\alpha\bar{\beta}}C^\alpha\bar{C}^{\bar{\beta}} + [Z_{\alpha\beta}(X, \bar{X})C^\alpha C^\beta + h.c.] \quad (34)$$

$$W = c + \mu^2 X + \frac{1}{6}\tilde{Y}_{\alpha\beta\gamma}C^\alpha C^\beta C^\gamma + \dots \quad (35)$$

In the above $\tilde{K}_{\alpha\bar{\beta}}, Z_{\alpha\beta}$, may of course depend on other moduli (which don't break SUSY) which are not explicitly written down. Also in W we take the standard model Yukawa coupling to be independent of X and the $\tilde{\mu}$ term to be zero. As in the previous discussion the potential will

⁵For a recent discussion see [19].

have a minimum at $X = X_0 = \frac{\sqrt{3}\Lambda^2}{6}$, $C = 0$, and the SUSY breaking will be characterized by $F^X \simeq \mu^2 = \sqrt{3}m_{3/2}$ after fine-tuning the CC as before. This scenario is of course a particular case of the situation we discussed before, and will yield FCNC conserving scalar masses and trilinear couplings (see equations (17)(18)). For example in the simplest case $g = X\bar{X}$ $m_0^2 = m_{3/2}^2(1 - 3\partial_X\partial_{\bar{X}}\ln g(X, \bar{X})) = m_{3/2}^2$. However one might expect that the particular structure of the Kaehler potential (i.e. the form of the third term in (34)) cannot be preserved when loop corrections are added. The dangerous terms are the quadratically divergent supergravity loop corrections. But to one loop order they have been calculated using the Coleman-Weinberg potential (see for example [20]). With the cutoff Λ the corrections to the squared scalar mass is of order

$$\frac{N\Lambda^2}{(4\pi)^2}m_{3/2}^2 \sim 10^{-4}m_0^2, \quad (36)$$

where in the last relation we used N the number of chiral scalars in the loop to be around 10^2 and the cutoff to be $\Lambda \sim M_{GUT} \sim 10^{-2}$. This estimate shows that the FCNC effects generated by these quantum corrections can be safely ignored since $\Delta m_{FCNC}^2/m_0^2 < 10^{-3}$. Similarly any FCNC effect in the trilinear couplings coming from quantum corrections is suppressed. Thus the boundary values used in mSUGRA are safe from large quantum corrections at the high scale, and as is well known the logarithmic RG evolution down to the weak scale will not generate any large FCNC effects.

The upshot is that once the embedding into supergravity is considered, there is no particular advantage in choosing GMSB over mSUGRA. Both require an ansatz about the coupling of MSSM visible sector to the supersymmetry breaking hidden sector. In GMSB one postulates an additional sector (the so-called messenger sector) which couples directly to the SUSY breaking sector and communicates the SUSY breaking via gauge interactions, which are of course naturally flavor diagonal. However SUGRA effects, which are always present, need to be suppressed way below the weak scale by tuning the gravitino mass to be extremely small. On the other hand in mSUGRA to get FCNC conserving initial conditions for the soft parameters, one needs to assume a particular type of coupling of the SUSY breaking moduli to the MSSM Kaehler metric. This may indeed be affected by quantum corrections at the high scale. However if the effective cutoff is well below the Planck scale (as is required to be the case in GMSB too) then these corrections are negligible.

Furthermore one needs to tune the gravitino mass only to the weak scale, and this immediately implies a natural solution to the μ and $B\mu$ problem, a feature which is absent in GMSB.

4 String theory considerations

String theory is supposed to be the ultra-violet completion of supergravity. Of course not every SUGRA may have such a completion so it is natural to favor those effective supergravity theories that have such a completion. Let us briefly review the general structure of the SUGRA that would emerge from a string theory compactified to 4 dimensions.

In both heterotic and type II models (compactified on a Calabi-Yau manifold Y) the Kaehler potential takes the the form

$$K = -2 \ln(\mathcal{V}) - \ln \left(i \int \Omega \wedge \bar{\Omega} \right) - \ln(S + \bar{S}). \quad (37)$$

Here \mathcal{V} is the volume of Y and depends on the Kaehler moduli, Ω is the holomorphic three-form on Y which depends on the complex structure moduli, and S is the dilaton-axion superfield whose real part essentially defines the string coupling.

As pointed out in [12] there are two typical cases: a) $F^S \gg F^M$, or b) $F^M \gg F^S$, where M is a modulus. In heterotic compactifications the axionic shift symmetry associated with S ensures that the superpotential is independent of it (except non-perturbatively). In this case one naturally gets mSUGRA soft terms with $m_0 \sim A_0 \sim M_i \sim m_{3/2}$ thus giving mSUGRA if case a) is realized.⁶ Unfortunately there is no known moduli stabilization mechanism that achieves case a).

In actual realizations of string theoretic SUGRA the opposite situation is what is obtained - i.e. in all known string compactifications (with fluxes and non-perturbative terms) which stabilize all the moduli, one finds that $F^M \gg F^S$ for at least one modulus. This is true of SUSY breaking in both heterotic and type IIB models that have been studied so far, and it is possibly a generic feature of string theoretic SUGRA. Thus it seems that the simple dilaton dominated SUSY breaking scenario, and hence the hope of having a model independent justification for mSUGRA discussed

⁶Estimates of string loop corrections to this dilaton dominated scenario are given in [21]. These imply that when FCNC constraints are taken into account the gravitino mass should be raised to about 400 GeV. This implies a small hierarchy problem, but this is in any case there in all SUSY mediation mechanisms because of the experimental lower bounds on the chargino and Higgs masses.

in the previous paragraph, is hard to obtain in string theory. Faced with this situation there are two options that one can pursue.

1. Choose flux configurations such that the gravitino mass is well below the weak scale and use GMSB.
2. Use large volume compactifications as in [22] (LVS).

There are several issues that need to be addressed before one can claim to have a viable string theory realization of GMSB. First one needs to tune the fluxes so that the gravitino mass is well below the weak scale. In typical GMSB models this is effectively a tuning of the SUSY breaking scale to be a factor of at least 10^6 below the SUSY breaking scale of mSUGRA or LVS models. In the landscape of string theory (since the frequency of models with zero CC and broken SUSY goes as F^6 [23]) this is less likely by factor of 10^{36} ! Even after selecting such a class of models one needs a supersymmetry breaking chiral scalar field X which must have a vev that is much smaller than the Planck scale (see above discussion after (31)). However in the (LVS) string theory regime in which meaningful calculations can be done with current technology (i.e. where the KK scale is well below the string scale which in turn is below the Planck scale), all moduli as well as the dilaton have vev's which are larger than the Planck scale. Thus we need another sector, the one represented by X in subsection (3.3).

In a string theory embedding one might think of supersymmetrically integrating out all the string theory moduli at a scale that is higher than the messenger scale $M_{messenger} \sim X_0 \sim \Lambda^2/M_P$, so that below this scale the system is well described by a model such as the one discussed in [17] (see discussion in subsection 3.3). Preliminary investigations [24] however seem to indicate that in order to produce a scale Λ which is parametrically smaller than the Planck/String scale $\Lambda/M_P \lesssim 10^{-5}$ as is required in GMSB, we need extremely large rank ($N > 10^4$) gauge groups to produce the requisite non-perturbative contribution to the superpotential that stabilizes the volume modulus at a large enough value. On the other hand the LVS scenario [22] does produce an exponentially large volume. However it also breaks SUSY dominantly in the volume modulus direction, and the corresponding light modulus (i.e. the sGoldstino) is lighter than the gravitino, so that it cannot be integrated out in GMSB where the gravitino is the LSP. Thus it appears

that one has to discuss the SUGRA potential involving at least the lightest modulus (typically the volume modulus) and the field X , and ensure that there is a minimum of the potential in the large moduli/dilaton region, which however yields a small value for the field X , even though they get F-terms of the same order i.e. $F \sim m_{3/2}M_P$. These requirements cannot be satisfied (see for example [25]) without fine-tuning.

The alternative is the LVS scenario of SUSY breaking [22][26][27][9]. Here the classical soft masses (and hence also the FCNC effects) are highly suppressed by powers of the large compactification volume, relative to the gravitino mass. All the moduli are stabilized by a combination of fluxes and non-perturbative effects. The gaugino masses are then generated by Weyl anomaly (AMSB) effects while the leading contribution to the soft scalar masses and the A term are generated by RG running effects [9]. With a soft mass scale at or below a TeV we need a volume which is at least 10^5 times the Planck volume in order that FCNC effects are sufficiently suppressed. The quantum effects are also suppressed relative to the classical terms by arguments similar to those given earlier (see eqn. (36) and references [9, 28],[29]).

A brief comment on the phenomenology of M-theory compactifications on G_2 manifolds (see [30] and references therein) is in order here. The soft terms are proportional to $m_{3/2}$ as in mSUGRA, however the gravitino mass is taken to be greater than $10TeV$ in order to avoid cosmological problems. Of course now the little hierarchy problem is somewhat worse (with a fine-tuning of at least one part in 10^4) and there is still an FCNC problem unless one makes a special ansatz as in mSUGRA.

Actually if one is willing to worsen the little hierarchy problem somewhat, one could solve the cosmological modulus problem within the LVS string theory derived inoAMSB scheme. According to [14] the upper bound on the gravitino mass is $m_{3/2} \sim 500TeV$. If we take this value then the resulting soft masses in inoAMSB are $(\alpha/4\pi)m_{3/2} \sim 2 - 3TeV$. This obviously increases the little hierarchy fine-tuning to one part in 10^3 , a factor of about 25 worse than in inoAMSB with $100TeV$ gravitino mass, but somewhat better than what one would have in the G_2 case above! The advantage of this $m_{3/2} = 500TeV$ version of inoAMSB is that now (as argued in [9]) the lower bound on the volume coming from the need to suppress FCNC is (in Planck units) $\mathcal{V} \gtrsim 10^4$ [9]. This means that the string scale $M_{string} \sim M_P/\sqrt{\mathcal{V}}$ can be as large as $10^{16}GeV$ allowing gauge

unification. Most importantly if we use this smallest allowed volume, the light modulus mass (i.e. the mass of the scalar partner of the Goldstino) is $M_{sg} \sim m_{3/2}/\sqrt{\mathcal{V}} \sim 5TeV$ thus possibly evading the cosmological modulus problem.

5 Conclusions

We have argued that any viable theory of SUSY breaking and mediation must be addressed within the SUGRA context and that conclusions drawn from a purely global analysis may not hold once the full implications of SUGRA are considered. The most important aspect that is missing from a purely global analysis is the issue of stabilizing the chiral scalar fields that are responsible for the supersymmetry breaking in such a way that the CC is (almost) zero. When these considerations are taken into account we argued that there is no reason to prefer GMSB over gravity or moduli mediated SUSY breaking in its various forms. If one also demands that such a supergravity be embedded in string theory, it seems that, while it is difficult to realize GMSB, and it is not clear whether the mSUGRA scenario can be realized either, the LVS type compactifications with anomaly and gaugino mediation, which give a viable phenomenology, can be obtained. The following table gives a rough comparison of these three main mechanisms highlighting the problems of each of them.

Table: Comparison Chart

	GMSB	mSUGRA	Sequestered
gravitino mass	$m_{3/2} \ll M_W$	$m_{3/2} \gtrsim M_W$	$m_{3/2} \gg M_W$
Mediation	gauge	gravitational	anomaly/gaugino
FCNC	natural	needs special ansatz	natural
$\mu/B\mu$	problematic	natural	possibly problematic
cosmo gravitino	OK	problematic	OK
cosmo modulus	problematic	problematic	problematic?
String embedding	hard	possible?	LVS example

Several comments are in order. Firstly FCNC suppression in GMSB is natural in that the main mechanism for mediating SUSY breaking are gauge interactions - however this requires the

suppression of the SUGRA mediation effects, and this is effected by looking at theories which have an extremely small gravitino mass. In sequestered theories the dominant mediation mechanism is the Weyl anomaly and gaugino mediation and the suppression of direct SUGRA effects is achieved in (LVS) compactifications of type IIB string theory by the large volume suppression of direct gravity coupling effects. The μ problem has been designated as possibly problematic since the μ -term depends on the terms which are responsible for the uplift of the CC, and though it is plausible that they may be generated at the right order, there is no precise calculation demonstrating that. The lightest modulus may also be problematic in this scenario unless one increases the gravitino mass to about $500TeV$, but this would worsen the little hierarchy problem .

Ultimately the correct mechanism may have to be decided by experiment. Nevertheless it is worthwhile investigating the theoretical questions posed in the last row of the table above. In particular while currently the only framework which allows a string theoretic description is the sequestered case in the last column, a definitive statement about the first two from the point of view of string theory, would give us valuable insights into the nature of physics close to the Planck scale, if the LHC reveals to us the existence of low scale SUSY and the structure of the soft SUSY breaking terms.

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